

# Metallic and insulating behaviour of the two-dimensional electron gas on a vicinal surface of Si MOSFETs

S. S. Safonov<sup>1</sup>, S. H. Roshko<sup>1</sup>, A. K. Savchenko<sup>1</sup>, A. G. Pogosov<sup>1,2</sup>, and Z. D. Kvon<sup>2</sup>

<sup>1</sup> *School of Physics, University of Exeter, Stocker Road,  
Exeter, EX4 4QL, UK*

<sup>2</sup> *Institute of Semiconductor Physics,  
Siberian Branch Russian Academy of Sciences, 630090  
Novosibirsk, Russia*

The resistance  $R$  of the 2DEG on the vicinal Si surface shows an unusual behaviour, which is very different from that in the (100) Si MOSFET where an unconventional metal to insulator transition has been reported. The crossover from the insulator with  $dR/dT < 0$  to the metal with  $dR/dT > 0$  occurs at a low resistance of  $R_{\square}^c \sim 0.04 \times h/e^2$ . At the low-temperature transition, which we attribute to the existence of a narrow impurity band at the interface, a distinct hysteresis in the resistance is detected. At higher temperatures, another change in the sign of  $dR/dT$  is seen and related to the crossover from the degenerate to non-degenerate 2DEG.

The problem of the metal-to-insulator transition (MIT) in two-dimensional systems has been attracting much attention after the observation that in the two-dimensional gas in (100) Si MOSFET there is a change in the sign of the temperature dependence from  $dR/dT > 0$  (metal) to  $dR/dT < 0$  (insulator) with varying concentration [1]. The transition occurs at a resistance of  $R_{\square} \sim h/e^2$  and was then confirmed to exist in other  $n$ -(100) Si [2] as well as in Si/SiGe and  $p$ -GaAs structures [3,4]. The metallic-like behaviour is in obvious contradiction with the 2D scaling theory of electron localization [5] which allows only insulating behaviour. The specifics of the unusual metal is in the fact that it has been seen in high mobility structures and at low concentration of carriers which have large effective mass, so that the Coulomb interaction could play a significant role. There have been many different explanations suggested [6] although this effect still remains an unresolved problem. Recently, several models have appeared where the unusual metallic behaviour is explained by conventional, though non-trivial, electron transport at low temperatures: i) classical conduction with scattering by an impurity band in the oxide [7], ii) temperature dependent screening of impurity scattering and crossover from the degenerate to non-degenerate state [8], iii) two-band conduction in  $p$ -GaAs [9].

In a broad temperature range from 50 mK to 70 K, we have performed an investigation of the MIT on the 2DEG in high mobility Si MOSFETs with *another* orientation of Si surface - the *vicinal* surface which is cut at a small angle to the plane (100). Such types of structure

have been studied previously in the context of superlattice effects [10–12] which were seen at higher electron concentrations than used in this work. We expected that the difference in the surface and impurity states at the interface would affect the manifestation of the MIT. Indeed, our results show that the MIT in the 2DEG of Si MOSFETs is *not universal* and has a different manifestation in the vicinal samples. We have observed *two* crossovers in  $R(T)$ , at low and high temperatures, which are explained in terms of the models [7] and [8] of the temperature dependent impurity scattering. The low-temperature transition has been seen at a small critical resistance where one can neglect quantum corrections to the conductivity. We have observed a strong hysteresis at this transition, which clearly indicates that it originates from a narrow impurity band (IB). We also report an unusual low-temperature reentrant MIT, which does not exist in (100) Si structures we made by the same technology for a comparative study.

The vicinal samples are high mobility  $n$ -channel MOSFETs fabricated on a surface which is tilted from the (100) surface around the [011] direction by an angle of  $9.5^\circ$ . The samples have a peak mobility of  $2 \times 10^4 \text{ cm}^2/\text{Vs}$  at  $T = 4.2 \text{ K}$ . The ‘normal’ samples are grown on the (100) Si and have maximum mobility around  $1.5 \times 10^4 \text{ cm}^2/\text{Vs}$ . The oxide thickness in both types of structure is  $120 \text{ nm}$ . The samples have a Hall bar geometry with length  $1200 \mu\text{m}$  and width  $400 \mu\text{m}$ . Their resistance has been measured in the temperature range  $0.05 - 70 \text{ K}$  by a four-terminal *ac* method with frequency  $\leq 10 \text{ Hz}$  and current  $2 \leq I_{ac} \leq 10 \text{ nA}$ . The electron concentration has been determined by the Shubnikov-de Haas and capacitance measurements, and has been varied in the range  $2 \times 10^{11} - 1.4 \times 10^{12} \text{ cm}^{-2}$ .

Fig. 1 shows the resistance as a function of the gate voltage  $V_g$  for a vicinal sample Si-4.1 in the temperature range below  $1 \text{ K}$ . A change in the sign of  $dR/dT$  is clearly seen near  $R_{\square} \sim 1 \text{ k}\Omega \sim 0.04 \times h/e^2$ , with metallic behaviour at larger  $V_g$ . When the gate voltage, controlling the concentration, is slowly swept (with rate  $2 \text{ V/hour}$ ) in the two opposite directions, two distinct groups of curves are detected. The hysteresis loop disappears above  $4 \text{ K}$  and seems to be most pronounced near the crossover region. To quantify this observation, we have performed an experiment where a particular  $V_g$  is approached from opposite directions: from  $V_g^{(1)} = 0.5$

$V$  and  $V_g^{(2)} = 9$  V. After a brief transient time when the equilibrium is established, the difference between the two resistances  $\Delta R = |R^{(1)} - R^{(2)}|$  is not changing for many hours. This value is shown in Fig. 1, inset, with a clear peak at  $V_g \approx 2.2$  V - exactly in between the two crossover points. The Shubnikov-de Haas measurements performed in each case have shown that, for a particular  $V_g$ , the electron concentration is independent of the direction of the sweep - that is, it is the difference in the mobility which gives rise to  $\Delta R$ .

Noticeably, the crossover point in the same sample does not have a universal nature: the two transition points do not coincide either in their resistance or concentration. On the other hand, the value of the mobility is practically the same at the transition points, which indicates that it is the mobility which governs the transition. Hence we suggest that the peak in  $\Delta R$  occurs when a narrow ( $W < 0.5$  meV) impurity band at the interface comes to the Fermi level of the 2DEG and changes the character of the electron scattering. A natural suggestion for the origin of the hysteresis is a slow (at low temperatures) electron exchange between the impurity band and the 2DEG separated by a barrier. With increasing  $V_g$  and rising of the Fermi level, the IB gets charged by electrons from the 2DEG. Some of the electrons will still remain in the IB when the gate voltage is decreased back to lower values, until the Fermi level is below the IB and it releases all its negative charge (this is why  $\Delta R$  is small both at high and low  $V_{gs}$ ).

It is worth mentioning that the presence of the IB was detected earlier in (100) Si MOSFETs [10], although this was done in the hopping regime, where it gave rise to an increased density of localized states and was easily detected as a peak in the conductance  $G(V_g)$ . Here its effect is seen on electron scattering in the metallic regime: as a crossover point in  $R(T)$  and as a peak in the hysteresis.

We suggest that the character of the IB is similar to that considered in [7]: it scatters electrons when it is positively charged and the scattering decreases when more electrons are added to it. In that model, when the Fermi level is above and close to the impurity band, the IB does not contribute to scattering at  $T = 0$  K. With increasing temperature, the IB becomes positively charged and the resistance of the 2DEG increases,  $dR/dT > 0$ . To explain the transition to the insulating behaviour with decreasing electron concentration, it was assumed that the electron localization takes over at large enough resistance of the order of  $R_{\square} \sim 10$  kOhm [13]. In our case, however, the transition occurs at much lower resistance where one can neglect electron localization. At the same time, we think that for a *narrow band* the crossover in the sign of  $dR/dT$  should occur when the Fermi level  $F$  is close to its centre. When the Fermi level moves down to the lower part of the IB, the mobility  $\mu$  will increase with increasing temperature, as the positive charge of the IB decreases as  $\mu^{-1}(T) \propto N^+ \propto 1 / (1 + \exp \frac{F-E_i}{k_B T})$ , where the IB is assumed to be at the level  $E_i$ , Fig. 2, inset. However, in

such a simple model one should not expect a decrease in the resistance by more than a factor of two.

Fig. 2 shows the temperature dependence of the resistance  $R^{(2)}$  near the transition at  $n_c \simeq 4.18 \times 10^{11} \text{ cm}^{-2}$ , in the range  $T = 50 \text{ mK} - 4 \text{ K}$ , presented as  $\mu^{-1}$  to illustrate this simple model of IB scattering. To calculate the IB contribution, we subtracted the background  $\mu^{-1}$  at  $V_g = 2.4$  V when the IB is full. The value  $F - E_i$  is calculated from known electron concentration and hence the Fermi energy  $E_F$ . The IB has been taken as having a constant density of states with width  $W \simeq 0.08$  meV used as an adjustable parameter. It is interesting to note that in order to get a satisfactory agreement, we have to shift gradually the level  $E_i$  up when the IB gets more than half filled. Also, the width of the IB appears to be smaller for the set  $R^{(2)}(T)$  (by a factor of two), that is, when the IB is more filled with electrons. We expect this to be a reflection of the Coulomb interaction of the states in the IB (to be discussed elsewhere [14]). It is important to emphasize that the ‘insulating’ behaviour presented in Fig. 2 for the resistance range  $R = 0.9 - 1.2$  kOhm is in fact a property of a metallic 2DEG with a well defined Fermi surface. A direct proof of this is obtained by measuring Shubnikov-de Haas oscillations at  $V_g = 2.0$  V - for a concentration below the transition.

Fig. 3 shows the temperature dependence in the whole temperature range. It is seen that the discussed low-temperature MIT at  $R \sim 1$  kOhm exists only in a narrow range of temperatures and that, in general,  $R(T)$  has complicated non-monotonic character. At  $V_g < 2$  V, the 2DEG shows an insulator which cannot be explained by the simple IB model and cannot occur due to the electron localization of a quantum nature because of the low sample resistance. This could be a result of a percolation-type localization. In Fig. 3, inset, the variation of the slope of the temperature dependence with decreasing  $V_g$  is shown for this insulator, using an exponential fit of  $R(T)$  in the range  $T \sim 1.5 - 7$  K. The activation energy  $\Delta = E_c - F$  is seen to increase linearly with decreasing Fermi level (calculated from the capacitance consideration). The activation energy extrapolates to zero at the mobility edge  $E_c$  corresponding to  $V_g = 1.9$  V - the value which is close to the lowest  $V_g$  where Shubnikov-de Haas oscillations were seen.

Let us discuss the behaviour of  $R(T)$  in Fig. 3 with increasing temperature. Localized electrons become delocalized at  $k_B T \geq \Delta$ , and after a dip in  $R(T)$  around  $T \sim 4$  K there is a change in the sign of the temperature dependence and the transition to metallic behaviour. At higher temperatures, another crossover is now seen at  $R_{\square}^C \simeq 3$  kOhm. Near this transition, there is a non-monotonic  $R(T)$  with a gradual change from  $dR/dT > 0$  to  $dR/dT < 0$  with increasing  $T$ . The phonon scattering can be neglected in this regime as it only becomes important at  $T > 100$  K [10]. We note that in the temperature range  $T > 4$  K the system experiences a transition from degenerate (quantum) to nondegenerate (classical) state (the Fermi temperature  $T_F$  varies from 90.5 K for the

bottom curve to 15 K for the top one in Fig. 3). The variation of  $T_F$  with concentration corresponds to the position of the hump in Fig. 3. All main features of the model [8] for the temperature dependent ionized impurity scattering can be seen in this regime. The metallic behaviour at  $T < T_F$  is explained in [8] by the temperature dependence of the screening function. This produces a linear rise in the resistivity with increasing temperature,  $\rho(T) \propto \rho(T=0) + A(T/T_F)$ , which agrees with experiment where  $\rho(T) \propto (T/T_F)^{1.1}$  for the bottom curve in Fig. 3. When  $T > T_F$ , the temperature dependence is expected to become  $\rho(T) \propto A(T/T_F)^{-1}$  due to ionized impurity scattering in the non-degenerate case which is in a qualitative agreement with upper curves in Fig. 3.

The further support of the classical to quantum transition at high temperatures is obtained from measurements of the perpendicular magnetoresistance. When  $T > T_F$ , we observed a small,  $\Delta R/R \sim 1-2\%$ , positive magnetoresistance. The magnetoresistance decreases with either increasing concentration or decreasing temperature, i.e. when the system is driven towards the degenerate state. This qualitatively agrees with the classical behaviour of degenerate semiconductors [15].

We have performed a comparative study of a normal sample (100) Si [14]. At high temperatures it also shows a crossover in  $R(T)$  but at a higher critical resistance,  $R_c \sim 15$  kOhm, and lower concentration,  $n_c \simeq 2.8 \times 10^{11} \text{ cm}^{-2}$ , than in the vicinal sample. The position of the resistance hump near the transition is shifted from  $T_F \sim 20$  K in the vicinal sample to  $T_F \sim 10$  K in the normal sample. This supports the applicability of the model [8] for the high-temperature transition in both samples. Comparing our normal sample with other (100) Si samples, one can see a similarity in the shape of  $R(T)$  near the transition, apart from the fact that the crossover in  $R(T)$  is shifted from  $T \sim 2$  K in [1] to  $T \sim 10$  K in our normal sample. If it is assumed that the transition in [1] can also be explained in terms of [8], the difference in the concentrations ( $n_c \sim 1 \times 10^{11} \text{ cm}^{-2}$  [1]) could account for the shift of the transition in the temperature scale.

At temperatures below 1 K, the normal sample shows a similar crossover behaviour as the vicinal ones, although no hysteresis has been observed, which does not allow us to link directly the low-temperature crossover around  $R \sim 1$  kOhm in the normal sample to an IB. In the metallic regime below  $R \sim 1$  kOhm, we have observed a striking difference between the vicinal and normal samples: in the vicinal samples there exists another crossover point at  $R \simeq 0.33$  kOhm and  $n \sim 8 \times 10^{11} \text{ cm}^{-2}$ , Fig. 4a. Re-appearance of the insulating state with increasing carrier concentration has been previously reported in (100) Si-MOS structures [16] and p-GaAs/GaAlAs [17] where it was attributed to weak electron localization. The effect we have observed on the vicinal sample is quite different from that in [16,17]. Firstly, it shows a significantly stronger (by a factor of ten) insulating  $R(T)$  which cannot be explained by weak localization. Secondly, the new

transition is accompanied by a hump in  $R(V_g)$  at base temperature, Fig. 4b. This feature, which we have seen in several vicinal samples, is possibly a manifestation of a gap in the energy spectrum which is only detected below 1 K. It is tempting to link this effect with a superlattice minigap, however this is usually seen at much higher concentrations  $\sim 2.5 \times 10^{12} \text{ cm}^{-2}$  [10,11]. Also, the reentrant insulator cannot be explained by occupation of the second subband [9] as we have not been able to identify its presence in the Shubnikov-de Haas oscillations and expect it to appear at higher electron concentrations [10].

In conclusion, we have observed several unusual features of the metal-to-insulator transition of the 2DEG on a vicinal Si surface and have been able to explain most of them by classical electron conduction with temperature dependent impurity scattering.

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Figure captions:

Fig.1. Resistance as a function of the gate voltage for sample Si-4.1 at  $T = 50, 153, 190, 237, 334, 391, 467, 583, 763, 850, \text{ and } 920 \text{ mK}$ . Two arrows show different directions of the  $V_g$  sweeps. Inset: the resistance difference for the two  $V_g$ -directions with a sharp maximum at the transition (a Lorentzian curve is given as a guide for the eye).

Fig. 2. Temperature dependence of the mobility near the transition at different electron concentration, from top to bottom  $n = 4.08, 4.12, 4.15, 4.19, 4.22, 4.25 \text{ and } 4.32 \times 10^{11} \text{ cm}^{-2}$  and corresponding gate voltages  $V_g = 2.1, 2.12, 2.14, 2.16, 2.18, 2.2 \text{ and } 2.24 \text{ V}$ . To separate the contribution of the IB, the background resistance has been subtracted; dashed lines show the theoretical fit. Inset: A diagram of the impurity band in the oxide giving rise to the metallic and ‘insulating’ behaviour of the 2DEG, with dashed lines showing the corresponding Fermi level positions.

Fig. 3. Resistance as a function of the temperature in the full range  $T=50 \text{ mK} - 70 \text{ K}$ . Electron concentration is changed from  $n = 1.85 \times 10^{11} \text{ cm}^{-2}$  to  $12.5 \times 10^{11} \text{ cm}^{-2}$  (bottom curve), with the gate voltage varied from  $V_g = 0.8 \text{ V}$  to  $V_g = 7 \text{ V}$ , respectively. The vertical line separates the low- and high-temperature transitions which are indicated by the arrows. Dashed line shows the Fermi temperature  $T_F$ .

Inset: Activation energy of the temperature dependence in the insulator as a function of the Fermi energy. Concentration is changed from  $n = 2.03 \times 10^{11} \text{ cm}^{-2}$  to  $n = 4.08 \times 10^{11} \text{ cm}^{-2}$  (bottom point) with step  $\Delta n = 0.65 \times 10^{11} \text{ cm}^{-2}$ ,  $V_g$  is changed with a step of  $0.1 \text{ V}$  from  $0.9 \text{ V}$  to  $2.1 \text{ V}$ .

Fig. 4. a) Resistance as a function of the gate voltage in the range of the reentrant transition,  $T=50 - 920 \text{ mK}$ . b) Temperature dependence of the resistance for different concentration changed with step  $\Delta n = 0.67 \times 10^{11} \text{ cm}^{-2}$  from  $n = 7.72 \times 10^{11} \text{ cm}^{-2}$  to  $n = 10.19 \times 10^{11} \text{ cm}^{-2}$  (bottom);  $V_g$  is varied with step  $\Delta V_g = 0.12 \text{ V}$  from  $4.22 \text{ V}$  to  $V_g = 5.66 \text{ V}$ , respectively.







